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THE INTERACTION OF A REFLECTED SHOCK WITH THE CONTACT SURFACE AND BOUNDARY LAYER IN A SHOCK TUBE

By

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19th September, 1961

'A.1' REPORT

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The Interaction of a Reflected Shock with the Contact Surface and Boundary Layer in a Shock Tube

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SUMMARY

In a hypersonic shock tunnel operated by the reflected-shock technique, the primary shock is reflected from the effectively-closed end of the driving tube, in order to provide a region of nearly-stationary shock-heated gas that can be used to supply the expansion nozzle, whose entry is located in the reflecting wall. The uniformity of this gas supply is affected by the motion of the reflected shock, and by disturbances that may pass back towards the nozzle entry after the reflected shock meets the contact surface separating the driving and driven gases. The simple theory of reflected-shock operation ignores viscous effects, and assumes that the contact surface is a plane discontinuity, whereas, in reality, the reflected shock moves back over the boundary layer formed after the passage of the primary shock, and the region separating the driving and driven gases may be non-uniform across the tube, and diffuse.

The present experiment was designed to investigate the effects of these departures from the simple theoretical model, by providing photographs illustrating the interaction of the reflected shock with the boundary layer and with the contact region. For this purpose it was convenient to use a shock tube of rectangular cross section, although it was recognised that mechanical difficulties would then restrict the pressure levels (and hence Reynolds numbers) to values below those usually employed in shock-tunnel practice. Results were obtained for representative values of primary shock Mach number, using hydrogen as the driving gas and nitrogen as the driven gas.

The work demonstrates that there are striking differences between the observed flows and those assumed in inviscid theory, and that there are associated discrepancies with the predictions of the theory. These are particularly marked in connection with the disturbances reflected from the contact surface, and with the motion of the shock transmitted through the contact surface when the primary shock Mach number is high. On the other hand, the motion of the contact surface, after meeting the reflected shock, is in reasonable agreement with theoretical predictions.

As far as the operation of shock tunnels is concerned, the results are not discouraging, especially at the "tailored" condition where there appears to be reasonable agreement with the promising predictions of theory. It is noted, however, that, because of the low pressure levels or rectangular cross section employed, the present results are in some respects dissimilar to those observed in other shock-tunnel investigations. Further research is required to clarify these matters.

1./

1. Introduction

In order to increase the flow duration in a hypersonic shock tunnel, it is frequently the practice[1,2] to reflect the primary shock from the effectively closed end of the driving tube, in order to provide a region of nearly stationary hot gas that can be used to supply the expansion nozzle. For the technique to be successful, the properties of the gas entering the nozzle must remain substantially constant, and factors leading to non-uniformity of the gas behind the reflected shock are, accordingly, of interest. The elementary theory is considered in Ref.3, where it is demonstrated that the shock-heated gas may be disturbed by the arrival of the expansion wave originating at the diaphragm, or by disturbances reflected from the contact surface when it is struck by the reflected primary shock. Although experimental evidence in support of the theoretical predictions is included in Ref.3, it is clear that the theory ignores several factors that may be important in practice. In particular, viscous effects at the walls of the tube are neglected, and these may affect the shock motion, and hence the properties of the shock-heated gas. It is also assumed in the theory that the contact surface is a plane discontinuity, and this may lead to errors in the properties of waves reflected from it.

In view of these uncertainties, it was felt that an optical study of the flow near the end of the tube would provide useful results, and the present investigation was undertaken.

2. Description of the Apparatus

The experiment was performed in the shock tube illustrated in Figs.1 and 2. The high-pressure chamber is of 5.5 in. internal diameter over most of its length, but the cross section changes smoothly to a 6 in. by $3\frac{1}{2}$ in. rectangle at the diaphragm position, and these dimensions are retained throughout the remainder of the tube. The diaphragm is held between flanges forced together by means of an hydraulic ram, and separated by return springs when the diaphragm is to be removed. For the present work, the diaphragm material was Mylar or aluminium, according to the required bursting pressure. To ensure that the aluminium diaphragms burst without fragmentation, grooves were formed in their surfaces by means of a press tool, and the shape after rupture is illustrated in Fig.2(b).

The working section contains glass windows spanning the full $3\frac{1}{2}$ in. height of the tube, and permitting the flow to be visualized by schlieren methods. In order to reduce the final pressure in the tube, a dump tank is normally connected downstream of the working section, but, for the present experiment, the tube was blocked within the field of the windows by the surface used to reflect the shock. Because of the associated reduction of volume, and the high pressures behind the reflected shock, the initial pressures had to be restricted to ensure that the safe loading (75 lb/sq in.) of the glass windows was not exceeded. The result was that the pressure levels of the experiment were considerably lower than those usually employed in hypersonic shock tunnels.

The velocity of the primary shock was inferred from the signals of thin-film shock detectors located in the wall of the tube upstream of the working section, and the pressure near the reflecting surface was measured with a transducer (S.L.M. PZ14) inserted in the wall of the tube (Fig.1). Single-exposure schlieren photographs were taken using a spark light source of duration approximately 0.2 microsecond above half peak amplitude, and wave-speed camera records were obtained with a drum camera and long-duration light source.

To avoid combustion at the contact surface, and to make the conditions of the experiment resemble more closely those of a perfect diatomic gas, nitrogen rather than air was used as driven gas. Hydrogen was used as driving gas throughout the investigation, and the driving and driven gases were both initially at atmospheric temperature.

3. The Predictions of Perfect-Gas Theory for Inviscid Flow

Detailed results of simple theory are given in Ref.3, but it is convenient to summarize the conclusions here for comparison with the experimental results described below. When the shock (termed the incident shock) strikes the contact surface, there is, in general, a transmitted shock, and a reflected disturbance which may be either a shock or an expansion wave, depending upon the initial conditions in the tube. For given driver and driven gases at specified initial temperatures, the disturbance reflected from the contact surface is of zero strength for one value of the Mach number of the primary shock. For hydrogen driving air, or nitrogen, both initially at atmospheric temperature, this value of the shock Mach number is approximately 6, and the predicted wave pattern is that sketched in Fig.3(b). The transmitted shock moves at the same velocity as the incident shock, and the contact surface is brought to rest after interacting with the shock. A contact surface arranged to produce no wave reflection is referred to as "tailored" in Ref.1, and the corresponding primary-shock Mach number is termed the "tailored" value.

If the shock Mach number is below the "tailored" value, the theory predicts the wave pattern of Fig.3(a). Here, an expansion wave is reflected from the contact surface, and the transmitted shock moves at a velocity greater than that of the incident shock. After meeting the shock, the direction of motion of the contact surface is reversed.

For shock Mach numbers above the "tailored" value, the predicted wave pattern is as sketched in Fig.3(c). A shock is reflected from the contact surface, and the transmitted shock moves more slowly than the incident shock. The velocity of the contact surface is reduced, but its direction of motion is unchanged.

Calculated values of the velocities and strengths of the waves indicated in Fig.3 are given in Ref.3, which also includes data on the successive wave reflections that occur between the contact surface and the end of the tube, when the conditions are not "tailored". Such calculations suggest that the reflected waves rapidly become weak, so that there are good prospects of obtaining approximately uniform conditions at the end of the tube (and hence at the entry to the expansion nozzle) even if the conditions are not "tailored". For this reason, the present experiment has been made not only at "tailoring", but also at primary-shock Mach numbers below and above the "tailored" value.

The effects of the expansion wave originating when the diaphragm bursts are discussed in Ref.3, and are not considered in detail here. It should, however, be noted (see Fig.8) that, although for shock Mach numbers of 6 and 8, the expansion wave does not reach the working section within the period of interest, this is not so at a shock Mach number of 4. Here, the reflected head of the expansion wave would be expected to overtake the primary shock shortly before reflection; the whole reflection process is, therefore, subject to interference by the expansion wave, and this should be borne in mind when interpreting the results. Because the shock tube is fitted with only a single diaphragm station designed for use at high shock Mach number, these conditions had to be accepted to provide qualitative results for relatively weak shocks.

4. The Experimental Results

The flow in the shock tube was found to be reproducible in successive runs, and it was, therefore, decided to use an individual run for each schlieren photograph, the delay between the detection of the primary shock and the operation of the light source being adjusted so that each photograph corresponded to a different position of the reflected shock. This procedure had the advantage of permitting a conventional schlieren system to be used instead of a Cranz-Schardin system. With the latter, difficulties would have arisen, for the present nearly two-dimensional flow, because of the difference in the direction in which the parallel light beam from each individual source traversed the working section. Examples of the schlieren photographs are reproduced in Figs.4, 5, and 6 for

primary-shock/

primary-shock Mach numbers of 4, 6 and 8 respectively. These photographs show the reflected shock, the contact surface, and the boundary layer. The times indicated represent the interval between the reflection of the shock from the end of the tube, and the operation of the spark light source.

These photographs provide a series of instantaneous pictures of the flow pattern over the full height of the tube, but it was felt that continuous distance-time records of the motion near the plane of the centre line would also be valuable. These were obtained by masking the windows of the working section so that only a central slit, 0.1 in. high, remained unobscured, and by using a schlieren system and wave-speed camera to record the wave motion. Typical results are reproduced in Fig.7.

The variation of static pressure at the wall of the tube close to the reflecting surface was recorded during each run, and typical traces are shown in Fig.8. These are compared with the predictions of inviscid-flow theory based on the observed positions of the contact surface.

Measurements made from photographs like those reproduced in Figs.4-7 have been used to plot Figs.9, 10 and 11 which show the wave and contact surface* motion on the centre plane. The predictions of perfect-gas inviscid-flow theory are included in these diagrams, the theoretical wave patterns being constructed using the observed position at which the contact surface meets the reflected shock.

5. Discussion of the Results

The features of greatest interest in the present investigation are the interaction of the reflected shock with the boundary layer of the tube wall, and with the hydrogen-nitrogen contact surface. These topics are discussed below.

5.1 Interaction of the reflected shock with the boundary layer

When the primary shock moves along the tube, a boundary layer is formed on the wall. The reflected shock thus moves back along the tube into a flow containing a uniform core and a boundary layer near the wall, the boundary-layer thickness increasing as the shock moves further from the reflecting wall.

Before discussing the present results, it is convenient to summarize the conclusions of a previous investigation[4] by Mark. When considering the theory of the interaction, he brought the reflected shock to rest by imposing on the system a velocity equal and opposite to that of the reflected shock. For the laminar boundary layers with which he was concerned, he then considered the flow incident on the stationary shock to consist of the mainstream, and a uniform wall layer moving at the wall velocity, and with a temperature equal to the initial temperature of the wall. The total pressure of the wall layer is then compared with the static pressure behind the shock; for low and high values of the primary-shock Mach number it is demonstrated that the wall-layer total pressure exceeds the pressure behind the shock, and it is concluded that the boundary layer can then pass across the shock without marked interaction. For intermediate values of primary shock Mach number, it is shown, however, that the total pressure near the wall is less than the pressure behind the shock. It is concluded that the boundary-layer flow can then no longer pass through the shock, but will be collected near its foot in a "ball" of fluid whose size will increase as the reflected shock moves down the tube. Thus, as the shock Mach number is raised from a low value, small interaction effects are expected at first, then stronger effects, and finally reduced effects.

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*The shaded zone represents the margin of uncertainty in determining the position of the <u>leading</u> boundary of the contact region from the photographs. It is probable that the thickness of the region exceeds the breadth of the shaded zone, but the photographs give little information on this point, because refractive index gradients associated with the mixing of the driving and driven gases are confused by gradients due to the turbulent motion of the driving gas.

For laminar layers (the evidence that they were laminar is discussed below), Mark demonstrates experimentally that these three régimes exist in practice, although, to achieve the final reduction of the severity of the interaction, he had to use argon diluted with air as driven gas. This is because the theoretically-predicted shock Mach number for the occurrence of the third régime increases as the value of γ is reduced. Thus, if a diatomic gas is the working fluid, the reduction of γ associated with the increased temperatures achieved with high shock Mach number makes it difficult to attain the third régime of flow.

For primary-shock Mach numbers of about 2, Mark found that, when the reflected shock had travelled a certain distance from the end of the tube, the scale of the interaction was greatly reduced; he attributed this change to the passage of the shock into the region of the boundary layer where the flow was turbulent. A Reynolds number was defined to describe the flow by analogy with the flow on a flat plate in a steady airstream. This took the form

$$R = \frac{\rho_w u_2 \, x\left(1 + \frac{U_S}{U_{RS}}\right) \frac{u_2}{U_S}}{\mu_w} ,$$

where ρ_w and μ_w are the density and viscosity at the wall behind the incident shock, u_2 is the velocity behind the incident shock, U_S is the incident-shock velocity, U_{RS} is the reflected-shock velocity, and x is distance travelled by the reflected shock from the end of the tube. By noting the conditions at which the severity of the interaction decreased, Mark deduced that the value of this Reynolds number at transition is approximately 1.5×10^6.

Turning to the present experiment, we would expect on the basis of Mark's results strong interaction with laminar layers. If, however, Mark's transition Reynolds number applies at the higher Mach numbers used here, transition would be expected to occur close behind the incident shock, so that almost all of our results would be for turbulent interactions. On the other hand, the present resistance thermometer signals suggest that at our higher Mach numbers transition occurs well downstream of the shock, so that the interaction is in fact laminar. A typical signal from a resistance thermometer located in the wall of the tube is reproduced in Fig.12, together with the point assumed to represent transition. From such records, the following values of the distance, d, between the incident shock and transition were derived:-

Table 1

Approximate Distances Between the Incident Shock and Boundary-Layer Transition

M_{S1}	p_1 mm Hg	d in.
4	20	5
6	7	8
8	2	12

Thus, with the exception of the results for $M_{S1} = 4$, it seems that the interactions illustrated* in Figs.4, 5, 6 are laminar at least until the contact surface is reached.

The results illustrated by Figs.4-6 are generally similar to Mark's observations for laminar layers, and to the general predictions of his simple theory. At the lowest shock Mach number illustrated by Fig.4, the interaction

is/

*The lengths of these photographs correspond (see Fig.1) to a distance of approximately 10 in.

is relatively weak, and there is some evidence of a thickened boundary layer well downstream of the shock. The results for the higher shock Mach numbers illustrated in Figs.5 & 6 show much more striking interaction effects. There appears to be no abrupt change in the character of the interaction after the shock has passed through the contact surface, although there is some reduction of the angle between the upstream limb and the wall. In most of the photographs, vortices appear to be present downstream of the shock, and to move round the wall towards the centre line with increasing time. It is clear, therefore, from this observation, and from other considerations, that the gas is not at rest behind the reflected shock, although it is possible that the velocities near the end wall are not sufficient to influence the pressure there greatly. For example, the observed pressure shown in Fig.8(b) remains substantially constant until the arrival of the reflected head of the expansion wave, as predicted by inviscid theory.

A factor of interest in the operation of reflected-shock tunnels is the effect of the boundary-layer interaction on the velocity of the reflected shock, because, if this is not constant, the pressure downstream will vary. For laminar boundary layers, and relatively weak shocks, Mark finds that there is attenuation of the shock immediately after reflection, followed by acceleration to a velocity approximating to that calculated for inviscid flow. The results of the present experiment do not permit the shock velocities to be derived accurately close to the reflecting surface, but it is seen from Figs.5 & 6 that, the mean velocities of the shock between the wall and the contact surface are considerably below the theoretical values. No conclusions can be drawn from the results for $M_{S1} = 4$ because of the effects of the expansion wave originating at the diaphragm. As discussed below, there is a general tendency for the shock to accelerate after it has travelled some distance from the wall, and at $M_{S1} = 6$ the final velocity is seen in Fig.10 to be close to the calculated value.

5.2 Interaction with the contact surface

It is seen from Figs.4, 5 & 6 that the contact surface bears little resemblance to the plane discontinuity envisaged in the theory, and there is, therefore, some difficulty in assessing its position from the flow photographs. Nevertheless, there is surprisingly good agreement between the observed and calculated motion of the contact surface after it meets the reflected shock, as can be seen in Figs.9, 10 & 11, and in the wave-speed camera records of Fig.7.

There is no sudden change in shock velocity as it passes through the contact surface. For $M_{S1} = 6$ (Fig.5) this is in accordance with the predictions of theory, but for $M_{S1} = 4$ and 8 a rapid change of velocity would be expected; in both cases the shock continues to accelerate after passing the contact surface, and the discrepancy with the theoretical result is particularly striking at $M_{S1} = 8$ (Fig.11), where a large reduction of shock velocity is predicted. In view of the very strong boundary layer interaction that occurs (see Fig.6), the disagreement with the theoretical result is not surprising, and it seems probable that boundary-layer effects dominate the flow pattern.

The photographs show no disturbances reflected from the contact surface, and attempts to visualize these by using a schlieren apparatus of greatly increased sensitivity were not successful, even though the sensitivity was such that a concentrated disturbance of the strength predicted by theory should have been detected. It is possible that, because of the nature of the contact surface, reflected disturbances are diffuse, or that their strength is modified by the departure of the velocity of the transmitted shock from that predicted by inviscid-flow theory. The pressure records reproduced in Fig.8 show, for a shock Mach number of 4, a steadily falling pressure after shock reflection due to the arrival of the head of the expansion wave from the diaphragm. For a shock Mach number of 6, the pressure is substantially constant, as predicted by theory. When the shock Mach number is raised to 8, there is a positive pressure gradient after shock reflection of the same order as that predicted by simple theory, but there is again little evidence that well-defined shocks are present.

6. Concluding Remarks

The work indicates the severity of the interaction that occurs with the boundary layer, and the diffuse nature of the contact surface. It might, therefore, be expected that the predictions of simple theory will be grossly in error, but it is found that there is surprisingly good agreement at the "tailored" condition, and for the contact-surface motion after meeting the reflected shock even at shock Mach numbers far from "tailoring". The most striking discrepancies lie in the absence of well-defined waves reflected from the contact surface under "non-tailored" conditions, and in the motion of the transmitted shock for strong primary shocks. Comparison with pressure measurements made with higher initial pressures in shock tunnels of circular cross section suggest that the present results may here be atypical, possibly because the boundary layer interactions in the former are turbulent. Thus, for example, disturbances reflected from the contact surface were readily detectable in the pressure measurements reported in Ref.3. Also, a marked fall of pressure near the end wall immediately after shock reflection that was observed in previous investigations[3], and attributed to the effects of attenuation of the reflected shock, is not observed in the present investigation.

Although, therefore, the results give a clearer impression than has previously been possible of the flow processes that occur close to the nozzle entry of a shock tunnel, it seems that further experimental work is required at pressures, and with a tube geometry, that are more typical of shock-tunnel practice. The development of an approximate theoretical treatment for turbulent boundary-layer interactions would also be of value. It is hoped that it will be possible to extend the work in these directions at a later stage, and to include a study of the possibility of provoking early transition to turbulent flow by means of excrescences attached to the wall of the shock tube used for the present investigation.

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No.	Author(s)	Title, etc.
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(2)	D. W. Holder and D. L. Schultz	On the use of shock tunnels for research on hypersonic flow. Second International Conference on the Aeronautical Sciences, Zurich, 1961.
(3)	D. W. Holder and D. L. Schultz	On the flow in a reflected-shock tunnel. A.R.C.22,152 - Hyp.130, 29th August, 1960.
(4)	H. Mark	The interaction of a reflected shock wave with the boundary layer in a shock tube. N.A.C.A. Technical Memorandum 1418, March, 1958.

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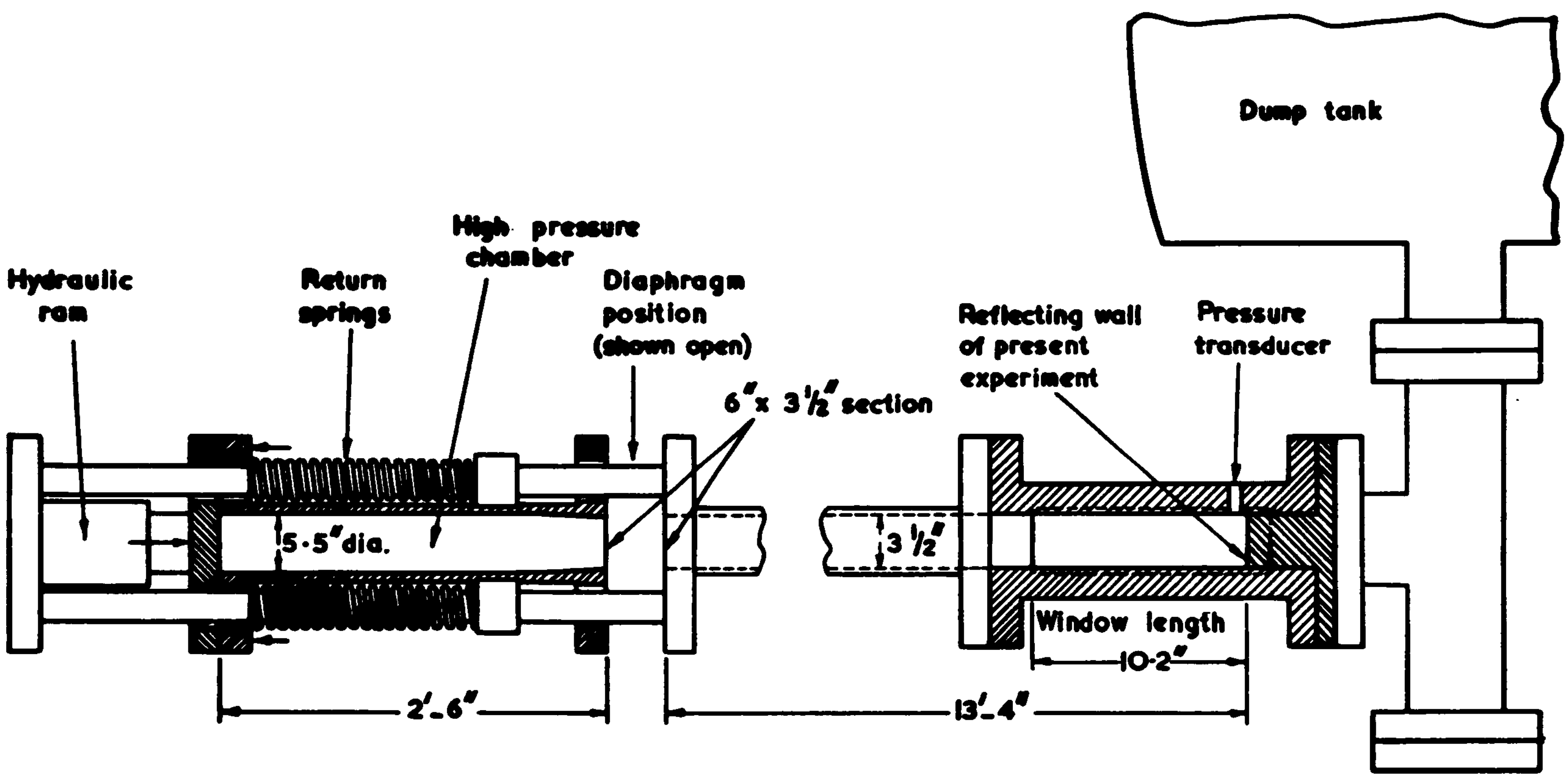
FIG. 1



Sketch of the 6" x 3½" shock tube (not to scale)

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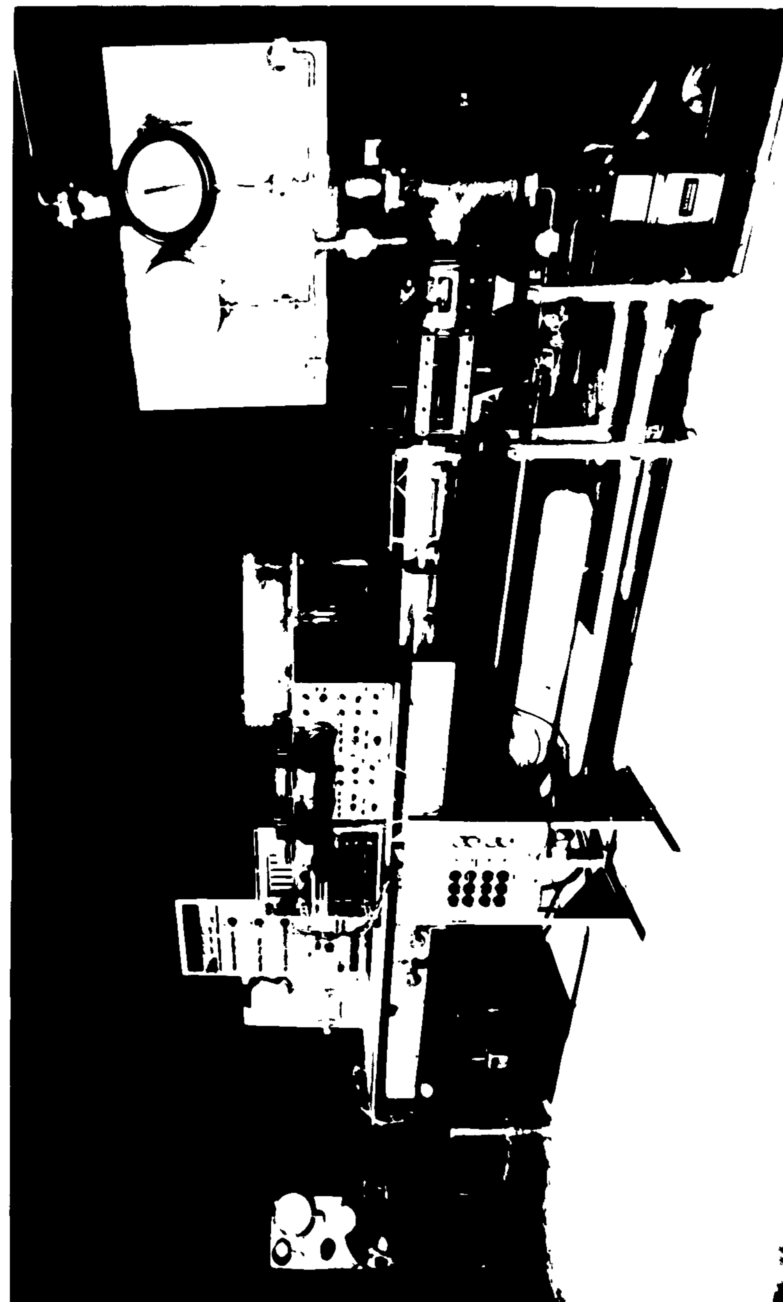
FIG. 2(a)



Photograph showing the general arrangement of the 6" x $3\frac{1}{2}$" shock tube

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FIG. 2(b)

Photograph showing the diaphragm section of the 6" x 3 1/2" shock tube, and the geometry of an aluminium diaphragm after rupturing.

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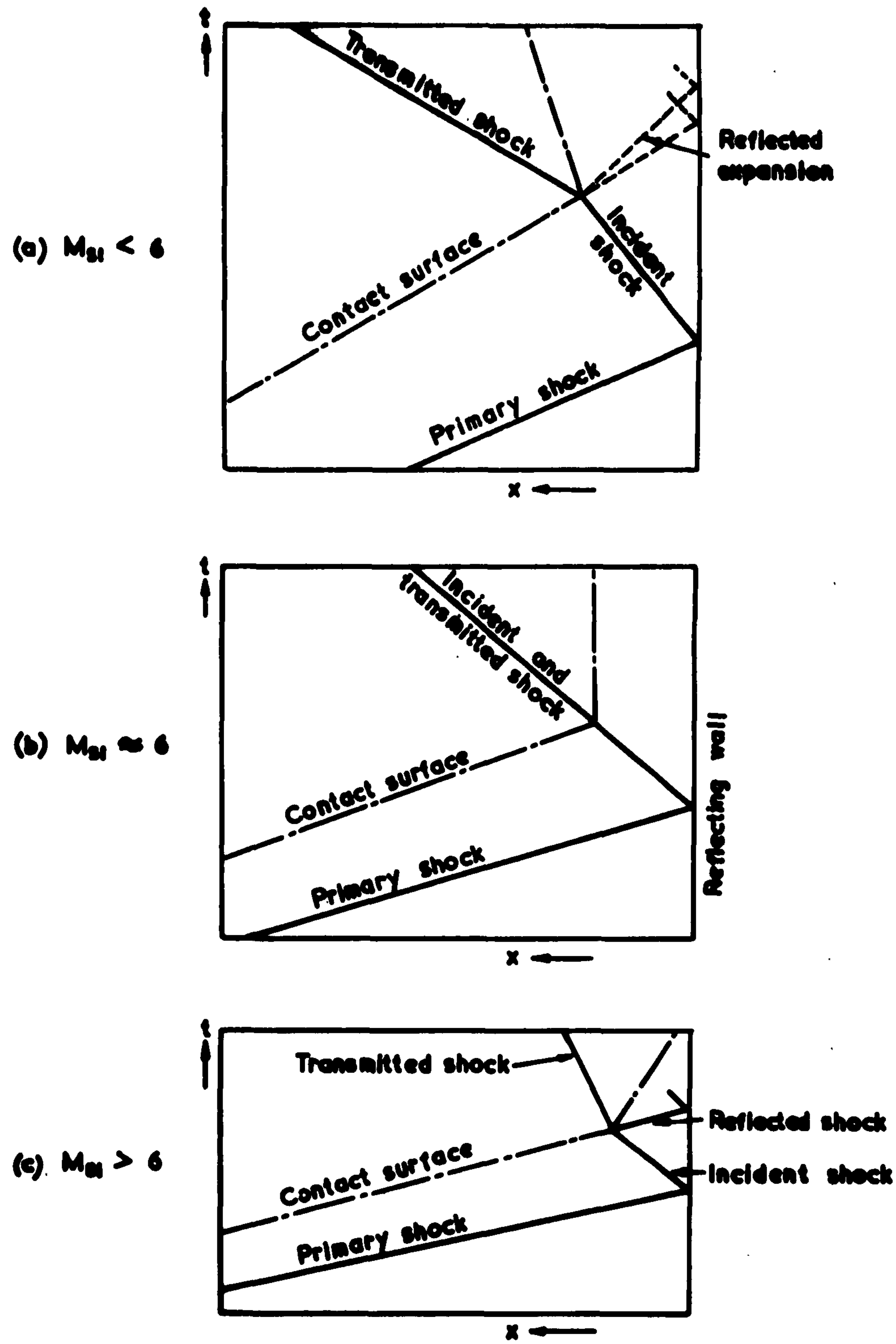
FIG. 3.



Theoretical wave diagrams for three values of the primary – shock Mach number M_{S1}.

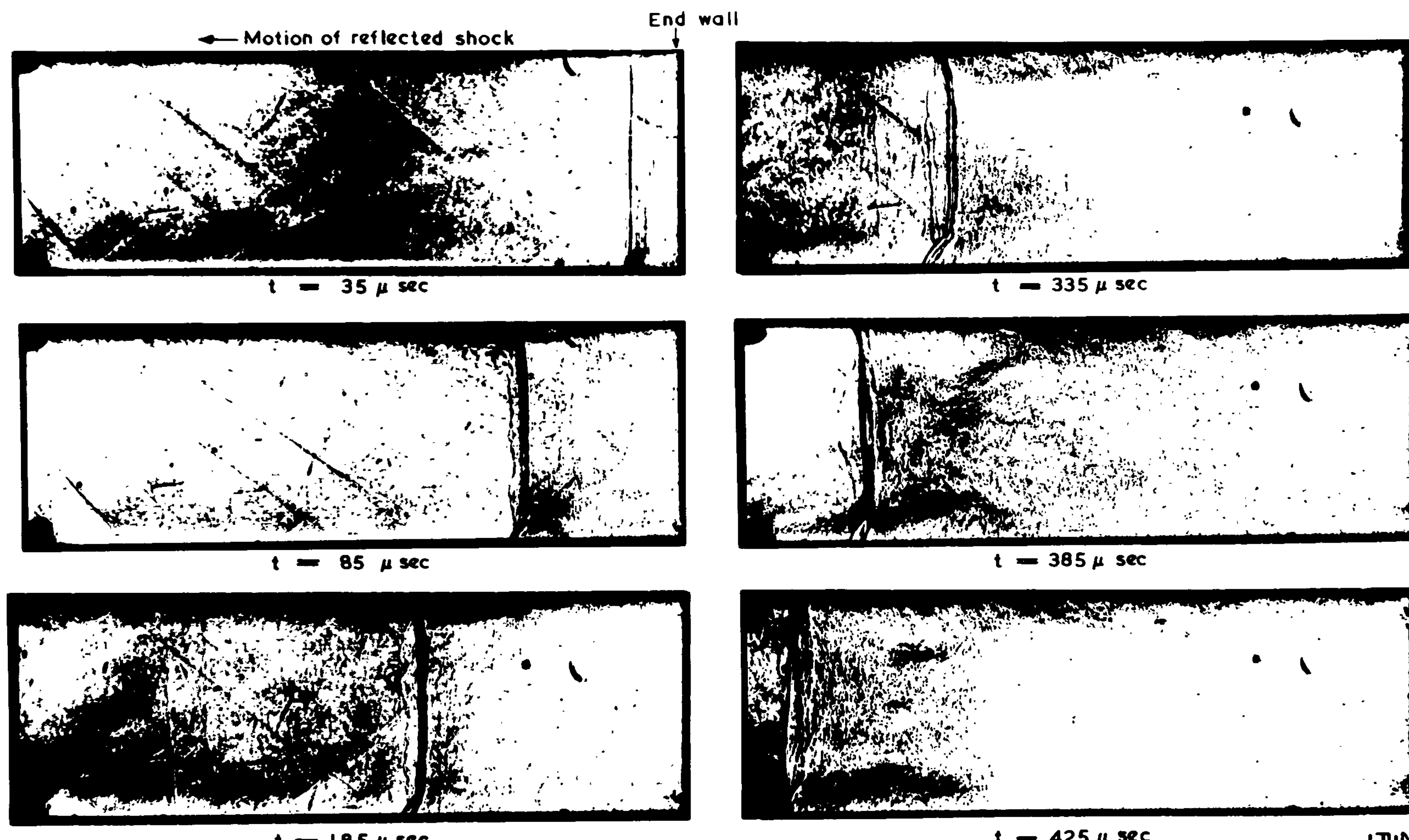


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FIG. 4

Schlieren photographs of the flow pattern for $M_{S1} = 4$, $p_1 = 20$ mm Hg
The times quoted are measured after the reflection of the shock from the end wall

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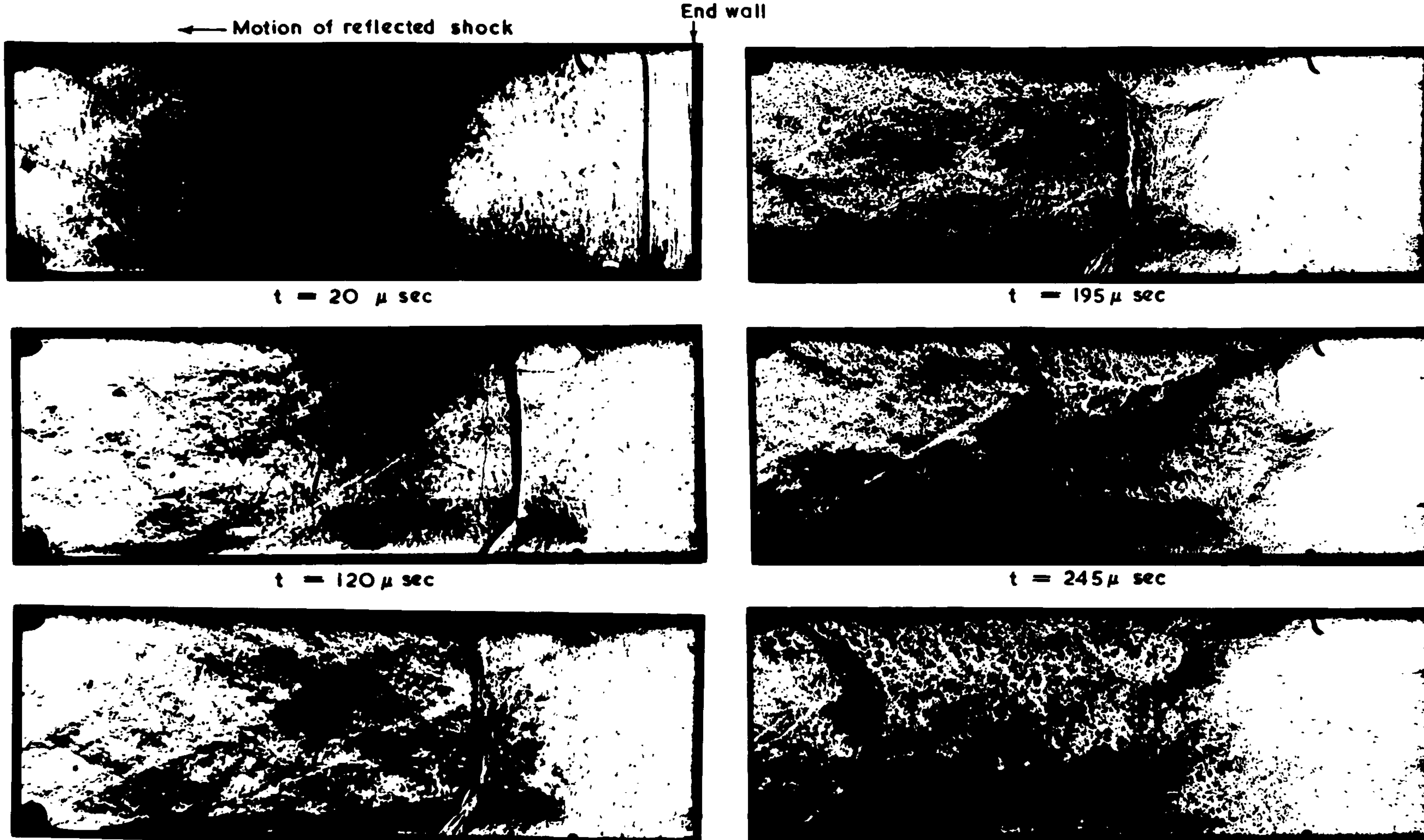
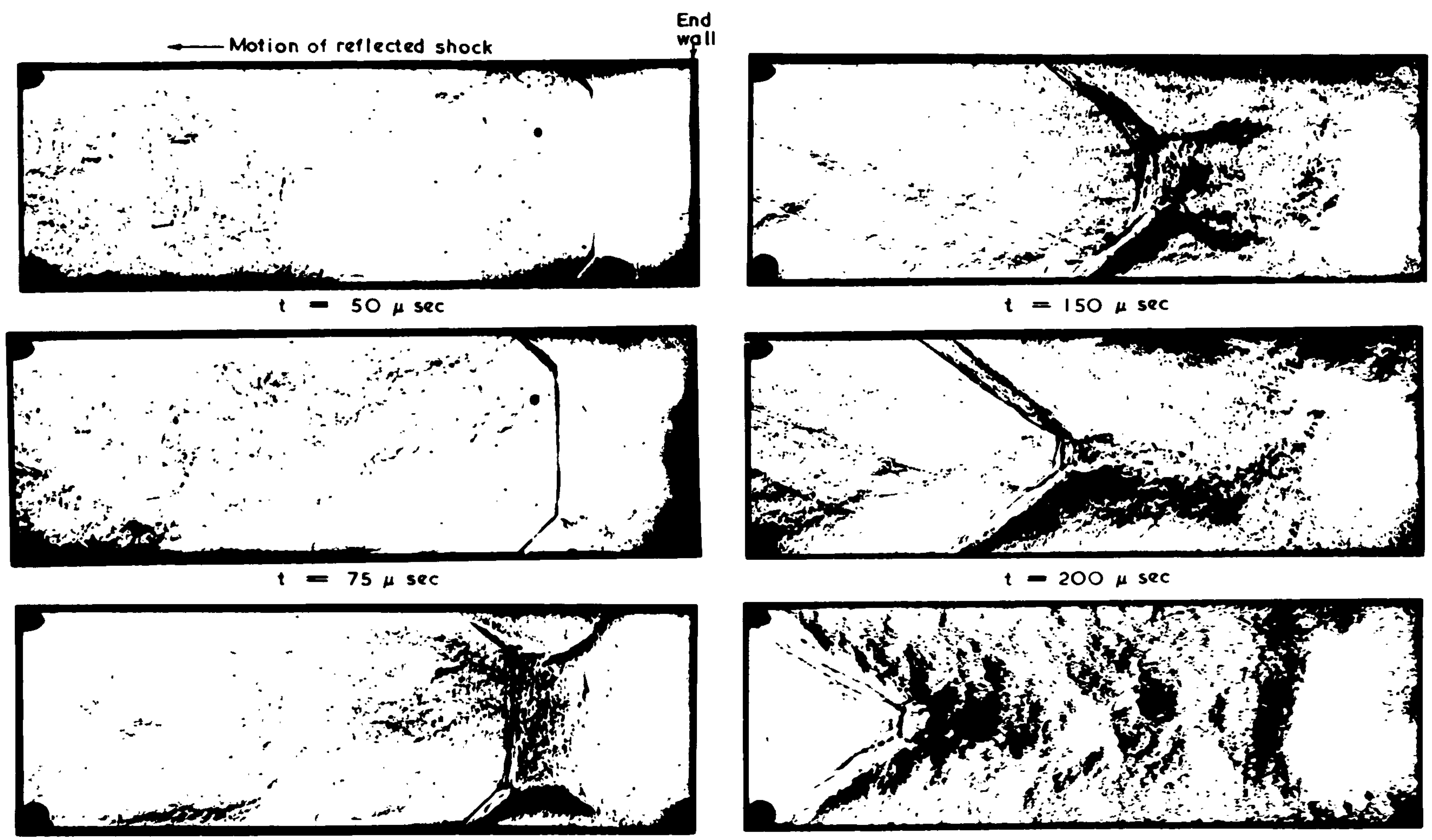
FIG.5



Schlieren photographs of the flow pattern for $M_{st} = 6$, $p_1 = 7$ mm Hg.

The times quoted are measured after the reflection of the shock from the end wall



$t = 50\ \mu$ sec

$t = 150\ \mu$ sec

$t = 75\ \mu$ sec

$t = 200\ \mu$ sec

$t = 100\ \mu$ sec

$t = 275\ \mu$ sec

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FIG. 6

Schlieren photographs of the flow pattern for $M_{S1} = 8$, $p_1 = 2$ mm Hg

The times quoted are measured after the reflection of the shock from the end wall

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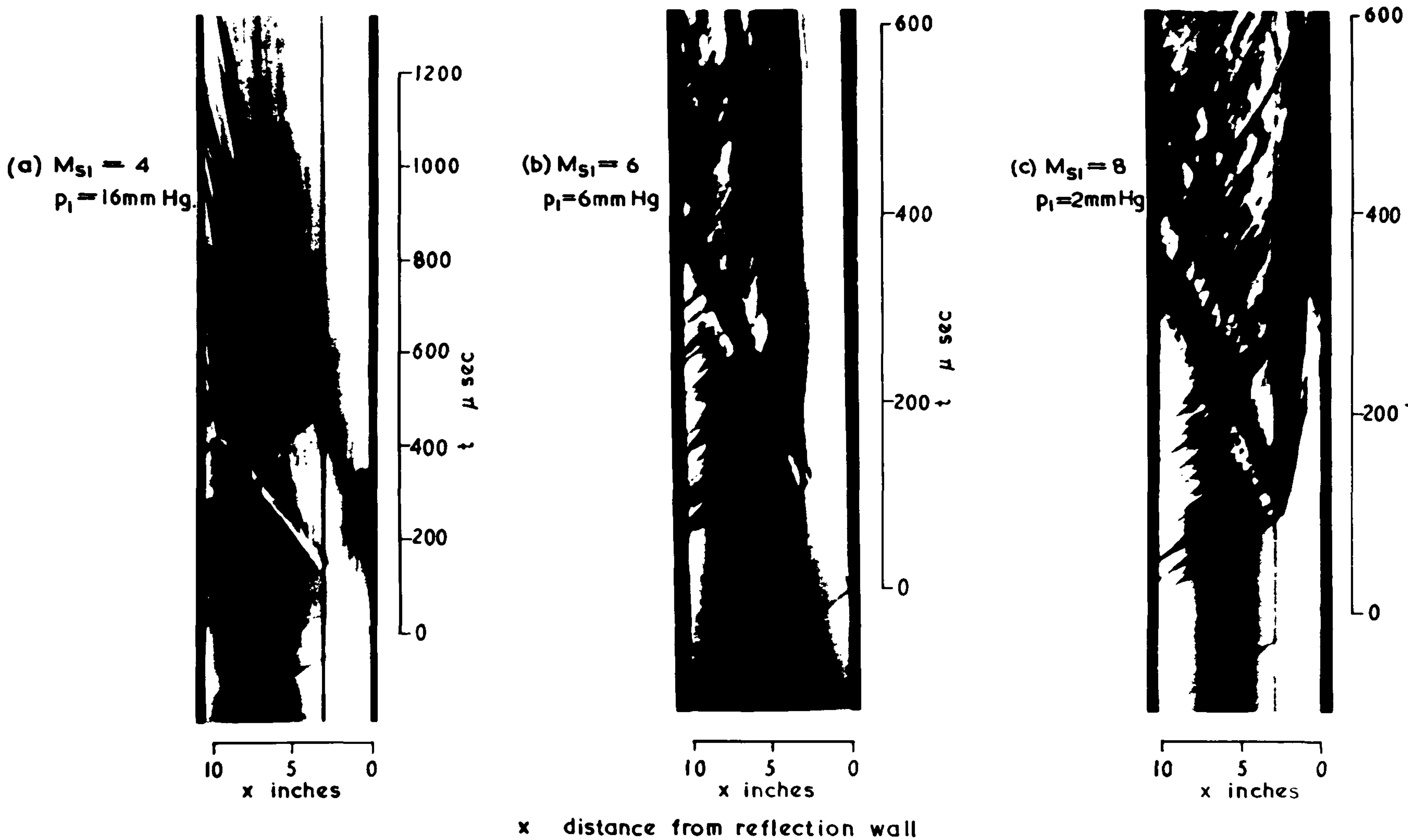
FIG. 7



Wave—speed camera records of the motion near the centre plane of the shock tube

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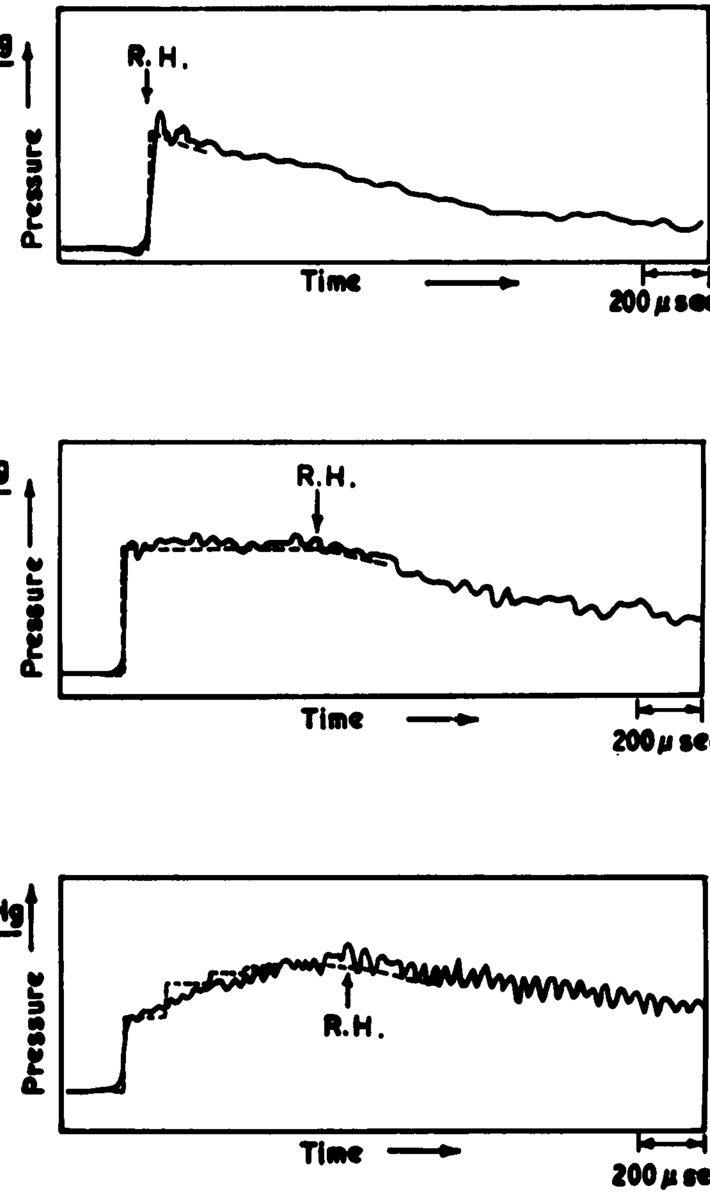
FIG. 8

(a) $M_{S1} = 5{\cdot}75$, $p_1 = 27$ mm Hg

Whole distribution subject to effects of reflected expansion wave

(b) $M_{S1} = 5{\cdot}9$, $p_1 = 7$ mm Hg

(c) $M_{S1} = 7{\cdot}7$, $p_1 = 1{\cdot}5$ mm Hg



Full lines represent observed pressure, broken lines predictions of theory, and R.H. time of arrival of reflected head of expansion wave

Typical pressure records near the reflecting wall

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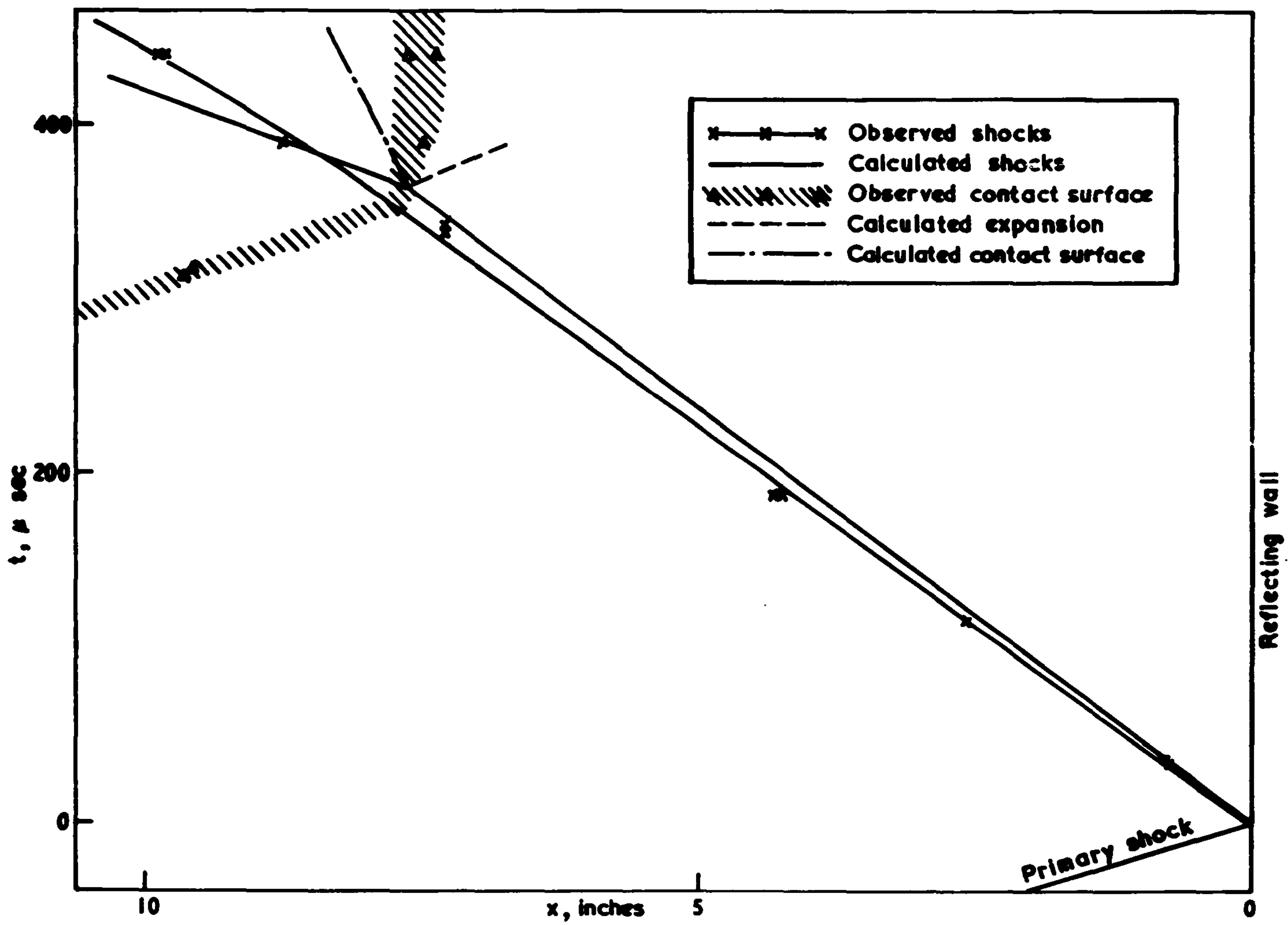
FIG. 9



Comparison between observed and calculated wave motions; $M_{s1} = 4$, $p_1 = 20$ mm Hg

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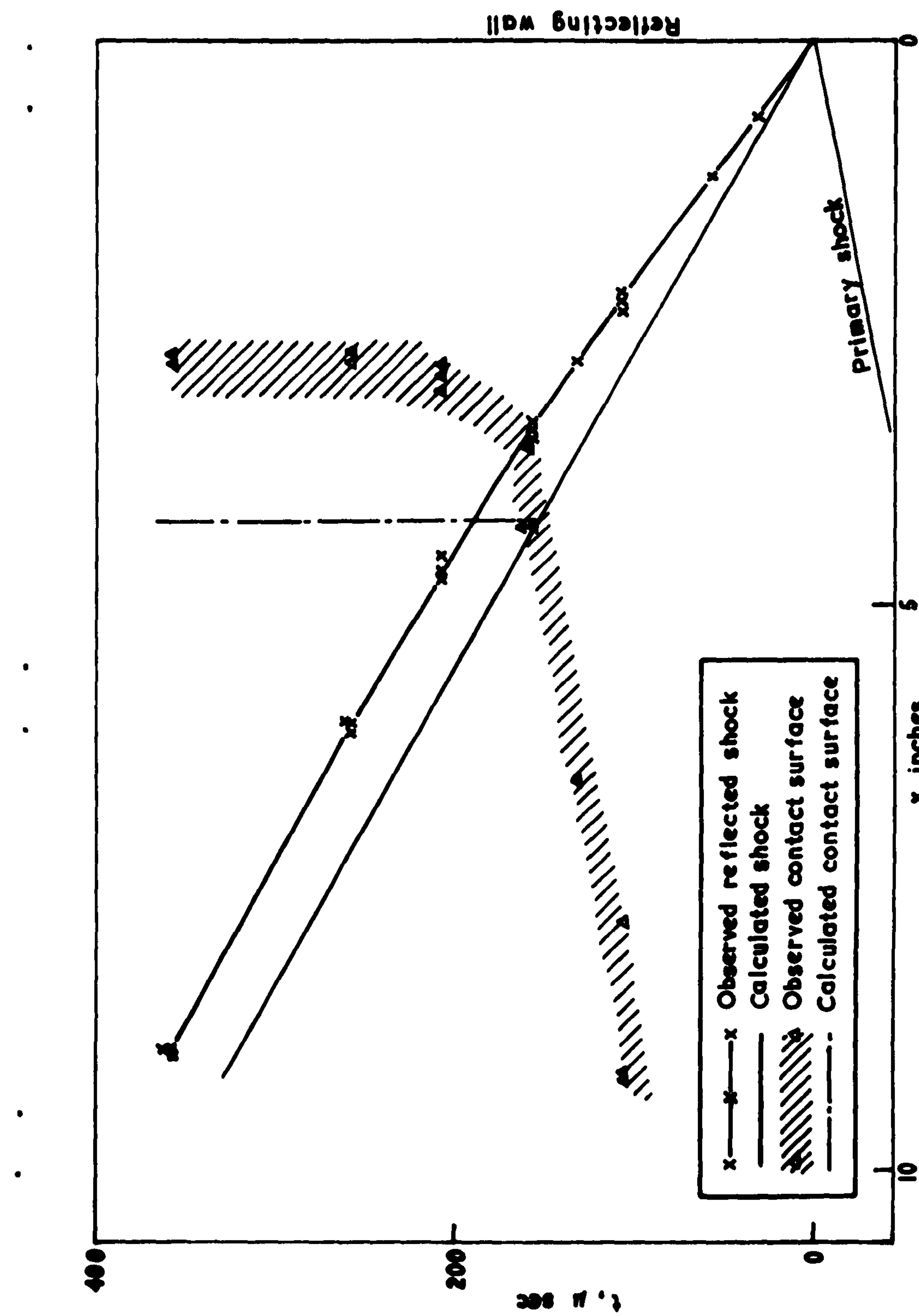
FIG. 10



Comparison between observed and calculated wave motions, $M_{s1} = 6$, $p_1 = 7mm$ Hg

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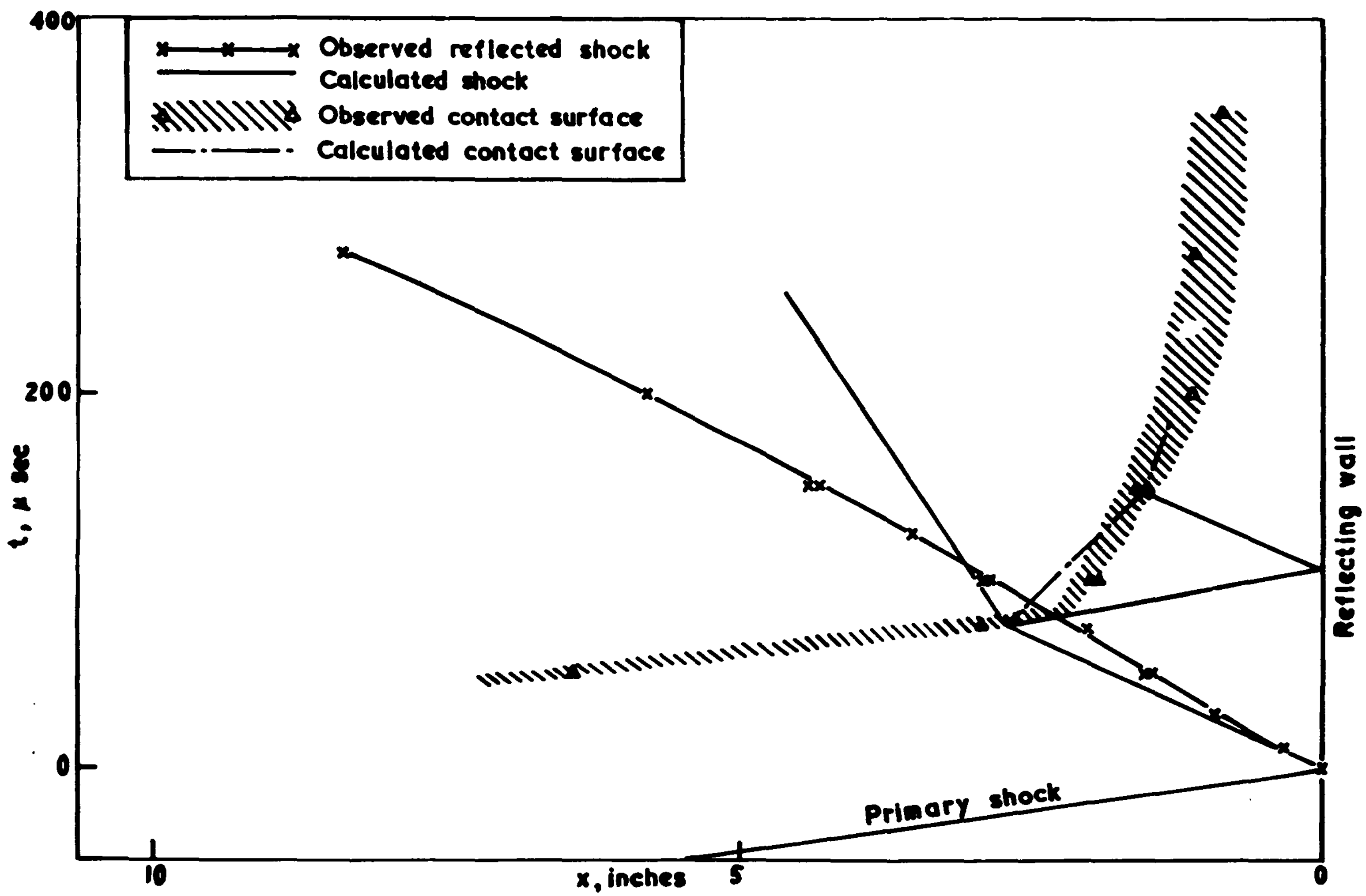
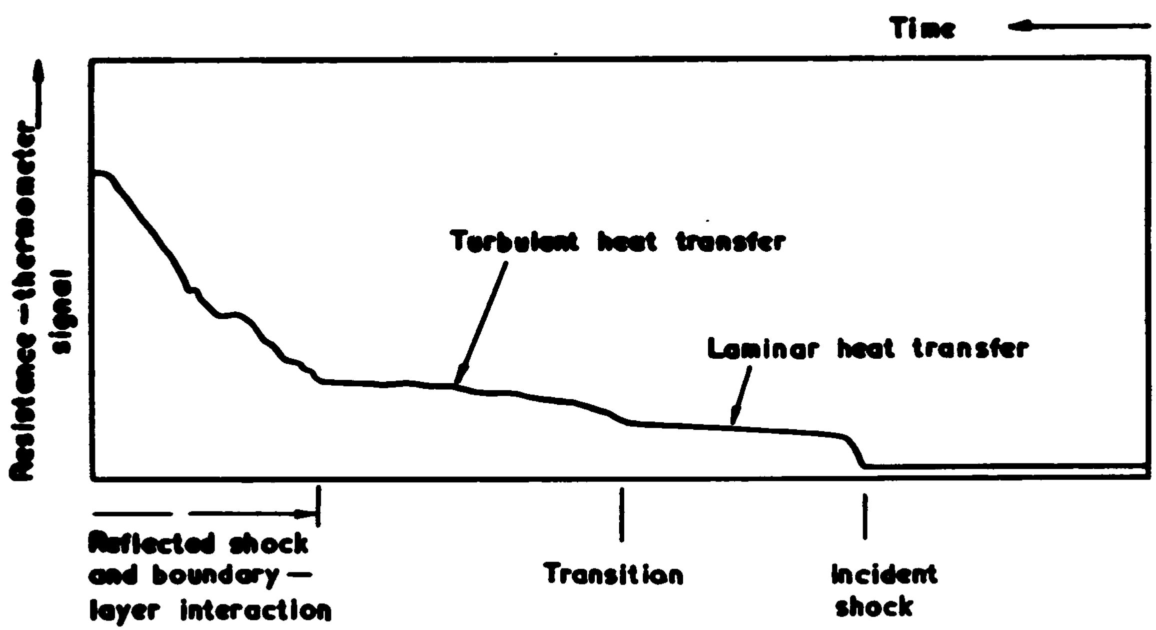
FIG. 11



Comparison between observed and calculated wave motions, $M_{S1} = 8$, $p_1 = 2$ mm Hg

FIG. 12.



Typical signal from resistance thermometer in wall of tube

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Holder, D. W., Stuart, C. M., North, R. J., Nat.Phys.Lab.

THE INTERACTION OF A REFLECTED SHOCK WITH THE CONTACT SURFACE AND BOUNDARY LAYER IN A SHOCK TUBE

The report contains the results of schlieren and wave-speed camera studies of the motion of the shock reflected from the closed end of a shock tube, and its interaction with the contact surface and the boundary layer on the wall of the tube. The driver and driven gases were hydrogen and nitrogen respectively, and the primary-shock Mach numbers ranged from 4 to 8.

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